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US INDUSTRIAL CAPACITY AND RISK-BASED SIMULATION FOR THE CONSTRUCTION OF THE MOBILE OFFSHORE BASE

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ABSTRACT

Several very large ocean structures have been proposed as part of the Office of Naval Research feasibility study of a Mobile Offshore Base (MOB). The MOB platform nominally is about 1500m (1 mile) by 129m (400 ft), which is unprecedented in size and operations compared to any floating structure to date. It is important to study constructability and industrial capacity issues to ensure a MOB could be built for a reasonable cost. The objectives of the constructability study presented in this paper were to establish the US capacity to build, provide a risk-informed construction feasibility assessment of, and quantify the construction cost and schedule for, five proposed MOB concepts. The US industrial capacity is quantified in terms of material production and shipyard and offshore fabrication capacities. The effects of safety, environmental, and management issues on production are also presented. Each concepts' cost and schedule was established and simulated using commercial simulation software to provide estimates that accounted for uncertainty and risks involved in the construction of a MOB.

Keywords: Risk-Based Simulation, Mobile Offshore Base (MOB), Construction Scheduling

INTRODUCTION

The MOB is a revolutionary structure due to its extremely large size and unique functions; thus building such a platform is a high-risk venture. The objectives of this paper are to: 1) quantify the US capacity to build a MOB and 2) assess the construction feasibility of a MOB by applying risk analysis techniques to obtain optimum costs and schedules for five proposed MOB concepts. The proposed MOB concepts are:

1. *Steel rigidly connected semisubmersible.* Proposed by Brown & Root [1] this concept consisted of six steel semisubmersible modules rigidly connected to form a MOB. Each module is 152m (500ft) in length by 92m (300ft) in beam. The total length of this MOB concept is 912m (3000ft).
2. *Steel hinged semisubmersible.* McDermott [2] has proposed a MOB concept that uses a hinged connection to link five modules together. These modules are 300m (985ft) in length, for a total MOB of 1500m (4925ft) long and 152m (500ft) in beam.
3. *Steel independent or dynamically positioned semisubmersible.* An independent module semisubmersible MOB concept was developed by Bechtel [3]. This concept has three modules that are 485m (1591ft) in length and 120m (394ft) in beam. The entire concept is 1455m (4773ft) in length.
4. *Flexible bridges between semisubmersible.* A proposal by Kvaerner [4] developed a MOB concept of three semisubmersibles linked together by two flexible bridge trusses. The semisubmersibles and flexible bridges are 258m (846ft) and 430m (1410ft) in length respectively, for a total MOB length of 1634m (5358ft) and a beam of 120m (394ft).
5. *Concrete and steel semisubmersible.* A proposal by Aker [5] developed a MOB concept of four linked semisubmersibles. The semisubmersibles consist of reinforced concrete hulls and columns with structural steel bracing and

decks. Each module is 380m (1246ft) in length and 152m (500ft) in beam. This MOB's total length is1520m (4984ft).

Major risks associated with MOB construction include cost and schedule overruns. Technical and technological construction challenges can be translated into increased cost and schedule demands. Should conditions prevail or events occur that lead to excessive costs, the MOB concept may prove impractical. Schedule risk is also critical because of the time value of money and because a MOB must be built within a reasonable amount of time to meet strategic goals.

For marine construction projects there are many factors that influence cost and schedule. Major sources of cost and schedule risks include labor, equipment, material, facility availability, third party delays, safety, changes in the design, and environmental compliance. Since labor cost is a significant portion of total cost, it can greatly influence cost and schedule due to non-availability, strikes, unskilled workers, or poor productivity. Having the appropriate materials on site at the right time influences construction schedules. The marine industrial infrastructure to support MOB construction is limited and the availability and throughput of these facilities can impact costs and schedules. Should a facility require expansion, a waterway require dredging, or offshore assembly be performed, environmental compliance will need to be addressed prior to any major infrastructure changes. Safety needs to be a major concern in the shipbuilding industry since it can be shown that this industry experiences a higher than normal injury and illness rate than similar industries. For these reasons, the following risks are identified and presented in this paper: cost, schedule, material availability, facility capability, labor availability, safety, environmental compliance, and construction management.

The primary focus of this study is the construction of the hull. The study only includes a generalized condition for outfitting of any of the MOB concepts since preliminary designs did not include or were extremely limited in outfitting details.

The methodology used in this study involves two levels of a feasibility assessment. The first is a qualitative initial assessment that defined the construction systems definition or requirements to build a MOB and the capabilities of US marine industry to build a MOB. By comparing these two findings an initial determination of feasibility is made and risk areas for further study were identified. The second feasibility assessments involved a much more rigorous risk analysis including modeling, simulation, and decision analysis.

MOB CONSTRUCTION

To bound the scope of this study, two construction scenarios were modeled and estimated for each concept. The first scenario utilizes as much of the current shipyard capacity as possible to produce MOB components, and assembly is performed at sea. The second scenario establishes a potential future major facility capable of dry-docking an entire MOB module to allow for terrestrial assembly.

Afloat Assembly Scenario

In the afloat assembly model, the hull and deck structures for each concept are broken down into large components to be constructed at shipyards on the East, West, and Gulf coast of the US. Over 40 facilities were considered as possible candidates to construct MOB components. Component construction at a particular location was based on: number of building positions, crane capacity, channel restrictions, location, labor strength, and experience in shipbuilding or repair. The major offshore industrial site at Aransas Pass, Texas was selected as the component erection site. This facility was chosen because of its capabilities and experience. Finished components would be assembled at sea offshore from this site. This area is subjected to weather that could cause delays in construction due to wave and or wind forces and, should a hurricane occur during assembly, a catastrophic failure or loss of a completed component may occur. The topic of weather risk analysis is addressed by Ayyub et al [6].

Terrestrial Assembly Scenario

This scenario was developed to investigate the effect of improving the infrastructure at a facility to enable a MOB module to be built ashore. This scenario has the added advantage of assembly without the weather risk that afloat assembly is exposed to. Having a facility with this construction ability will also provide a facility to perform future maintenance on a module. The ability to perform maintenance of the module and embarked equipment ashore may reduce the lifecycle costs of a MOB. A facility of this type does not exist today but could be built at several locations along the East and Gulf coast with a nominal size of 365m (1197ft) long by 152m (500ft) wide [6]. Facility expansion of this magnitude would most likely be funded as part of the total cost of a MOB and is not unprecedented as part of major Department of Defense procurements.

US INDUSTRIAL CAPACITY TO BUILD A MOB

An extensive literature review of construction techniques, coupled with meetings with MOB Program personnel and individuals in the marine, offshore and construction industries related to the MOB, was conducted to quantify the construction systems relevant to the MOB and the capacity of the marine and offshore industry. Tours of the shipyard at Baltimore Marine Industries, offshore construction facilities of Brown and Root and Aker Gulf Marine were conducted and data were collected. A baseline of the construction, marine and offshore industry's ability to construct the MOB was defined, and is documented in this section.

Material Production Capacities

The US produces a vast amount of steel. The type of steel that is consumed by the shipbuilding industry is shown in the second row of Table 1 [7]. A comparison of the material available or that can be produced by the steel industry and the steel needs for all concepts revealed that steel availability will not be a critical issue in the construction of a MOB. It was determined that the amount of steel produced in the US is an order of magnitude larger than the steel required to build a MOB.

Annual steel requirements for the rigid, hinged, flexible bridge, and steel and concrete concepts were conservatively estimated by assuming these concepts annual steel consumption during construction is equivalent to one module built per year. The independent concept is assumed to require 50% of the steel required in one module per year because this concept has modules so large it could not reasonably be built in a single year. When compared to total US steel production, a MOB's steel consumption during construction is extremely small.

Table 1. Steel Used in Marine Industry and Compared to Five Concepts Steel Requirements in Thousands of Metric Tons

Annual Steel Requirement 1997	Total shipments
All Industries	64,968.0
Shipbuilding	311.9
Rigid Concept	53.0
Hinged Concept	170.0
Independent (50% a year)	120.0
Flexible Bridge, semi	183.0
Flexible Bridge, truss	189.0
Steel & Concrete (upper hull)	90.0

The Aker concept is based on using reinforced concrete as the primary construction material for the columns and lower hull structure. The availability of base materials for concrete should not pose a resource problem to MOB construction because a large batch plant could be erected for a project of this size and materials, if not immediately available, will likely be available by barge.

Shipyard Production and Fabrication Capacities

The US shipbuilding industry is expected to perform the majority of the welding, erection, and fabrication of the MOB since this is where the equipment and labor expertise resides. The US shipbuilding capacities are quantified and compared to the MOB construction resource requirements. This study considered only US shipyards because the MOB would be a Department of Defense acquisition and would likely be required by law to be constructed in the US.

Other types of industrial facilities may be able to support the production for some of the smaller components, such as the braces or the smallest of the block components. These types of facilities may also have work subcontracted to them by a shipyard. This study recognizes that these facilities exist but no attempt was made to quantify their capacities due to the large number of such facilities and difficulty in quantifying production output.

Shipyard Capacities

There are 18 major shipbuilding facilities in the US with the capability to construct, drydock, and/or repair vessels with a length overall greater than 122 meters, provided that water depth in the channel to the facility is at least 3.7meters [8]. Additionally there are 31 other shipyard facilities with the ability to repair drydock vessels but typically do not build ships, with a length overall greater than 122 meters, and have a water depth of at least 3.7 meters [8]. The total of these two types of facilities is 49 shipyards that potentially could construct at least part of a MOB.

From these 49 shipyards, 42 are identified as practical facilities to construct portions of the MOB. These 42 shipyards include repair shipyards with large drydocks and large labor forces that could construct at least the braces for the MOB. Additionally other considerations such as past experience, channel restrictions, physical size, crane capacity, assembly areas, covered work areas, number of heavy lift capacity cranes, flat panel line output, and lengths and widths of panel production facilities, and drydock capacity were considered when determining a facilities ability to build at least the smallest MOB components. For a complete tabular listing of US shipyards and their ability to construct a MOB the reader is referred to Ayyub et al [9].

There is ample facility capacity at US shipyards to construct a MOB. The size of the components will determine which shipyards can participate and to what extent. Major shipyards with heavy lift capacity will produce a majority of the components of a MOB. Yet smaller shipyards with building positions would most likely be used in most construction scenarios. Construction models and estimates to build a MOB were developed that used between 11 to 20 shipyards. It was felt that 20 shipyards were the maximum number of shipyards that could be comfortably managed and coordinated to deliver components for a MOB.

Shipyard Labor

The labor demands of MOB construction appear to be a potential risk area due to the magnitude of the MOB project and declining skilled work force. However, an examination of US Navy ship construction data in the 1980s revealed that skilled labor in shipyards can surge to meet an increased demand, and that for the near future excess labor exists.

Prior to the Navy build up of the 1980s, US shipyards were only producing a few ships a year for the Navy. In the 1980s the US Navy was striving to develop a 600-ship fleet. US shipyards were producing an average of 19 Navy ships a year during the mid 1980s. Additionally commercial orders for ships increased from 0 in 1979 to 5 in 1985. A labor force that expanded and a more efficient industry accomplished this surge in shipbuilding activity.

In order to quantify the shipyard workers available, projections are made from published data on shipyard workers. The total number of personnel employed at private shipyards in the US during 1997 was 90,000 [10]. Of this, about 20,000 of these workers are projected to work on Navy shipbuilding projects and about 7,000 workers are projected to work on ship repair and non-shipbuilding functions [8]. Subtracting 27,000 from the 90,000 leaves about 63,000 workers available for commercial or unpredicted Navy work from all shipyards in the US.

Also 18 of the largest shipyards in the US employ approximately 60,000 equivalent production workers [8]. Of the 60,000 workers about 20,000 of those are projected to be employed by Navy funded construction and 7,000 employed in repair and non-shipbuilding work. This leaves about 33,000 workers at the major shipyards that are available for commercial ship construction or unpredicted Navy work. From these data sources, it appears that between 33,000-63,000 shipyard workers are potentially available for employment to build a MOB. This number of shipyard workers available for building a MOB is conservatively low because if a MOB were to be built some Navy shipbuilding could get deferred, thus providing more labor for MOB production.

An estimate of the number of workers required to build a MOB is derived from current Navy ship production data [11] and US Maritime Administration (MARAD) employment figures [8]. In 1997 an estimated 188,870 metric tons of Navy ships were produced by an estimated 20,000 workers, this equates to 9.44 metric tons per worker each year. This figure is derived from ship production data obtained from MARAD, and can only be applied as a rough guide. An additional productivity figure for shipbuilding is provided by Aker [5] as 48.8 metric tons per worker each year. These two productivity indices most likely bound the range of productivity. The wide range between the two productivity values may be due to Navy construction (high overhead & military specifications) compared to some of the most productive shipbuilding in Europe. The productivity indices used were strictly based on weight and did not allow for the length or size of MOB components.

Table 2 applies the annual tons of steel required for each concept and the Naval Sea Systems Command (NAVSEA) and MARAD derived figure to estimate annual work force requirements. Due to the approximate nature of available data a 50% mark up was applied to available worker data presented earlier to arrive at the figures in Table 2. For example, from Table 1 the hinged concept requires 53,000 metric tons of steel. Dividing this value by 9.44 metric tons per worker, the hinged concept requires 5614 workers. This value is multiplied by 1.5 and rounded to the nearest 100 to find the number 8,400 workers per year in Table 2. These figures indicated that labor would be a critical factor but would not prevent a MOB from being constructed.

Table 2. Adjusted Comparison of Shipyards Workers Required to Available

Concept	Workers required/ year	Available workers/ year.
Rigid	8,400	16,500 to 31,500
Hinged	27,000	
Independent	19,000	
Flexible Bridge	29,100	
Steel and Concrete	14,300	

Offshore Industry's Construction Capacity

The offshore industry is composed of many builders, suppliers, specialty contractors, subcontractors, and other related industries. This paper only presents the three largest, US based, worldwide constructors for the offshore industry, namely: Aker Gulf Marine, the J. Ray McDermott company and Kellogg Brown and Root a subsidiary of the Halliburton Company. Although many other offshore constructors exist, these three establish the upper limit in terms of single facility capacity and heavy lift ability.

The Aker Gulf Marine US facilities are located at Ingleside and Aransas Pass, TX. The large structure assembly yard at Ingleside is a 220-acre site on the Corpus Christi Ship Channel (CCSC) with unrestricted deepwater access to the Gulf of Mexico (GOM). The Aransas Pass yard is a structure fabrication facility also located on the CCSC and located about 3 miles from the Ingleside yard. These facilities have extremely heavy lift capabilities and employ about 1200 people.

The J. R. McDermott US facilities are located at Morgan City, LA and Aransas Pass, TX. The main building yard at Morgan City is a 589-acre site that is primarily used as a building and loading site. The Aransas Pass facility has been used to assemble some of the largest offshore structures that have been installed in the GOM. The Morgan City facility employs about 1000 people.

The Brown & Root Energy Services US facilities are located at the Greens Bayou fabrication yard just outside of Houston TX. It has fabricated large steel structures for the offshore industry and employs about 900 people. For example in 1999 it was constructing a topsides unit for a major customer. This unit has three, 61m x 61m levels and weighs 12,300 metric tons.

Each offshore construction facility is capable of erecting, assembling smaller blocks into large grand blocks of the upper hull, and loading the grand blocks onto barges for offshore assembly to the lower hull and columns of a MOB. Due to the weather sensitive nature of offshore assembly a weather window or "season" exists for assembly of grand blocks to the lower hull structure. Based on the scale of the combined three facilities, certainly in conjunction, the three could build, launch, and assemble the grand blocks of a MOB in a season. Each site is analyzed to determine if it could by itself build, launch and assemble the required number of grand blocks to complete a single MOB concepts module during a season. Table 3 presents a qualitative judgement if a single facility could erect, load-out, and assemble a concept's grand blocks during a single season. This qualitative judgement is based on a concepts' size and number of grand blocks compared to a facility's; size, waterfront and transportation abilities, employment, number and capacities of heavy lift cranes.

Offshore Labor

The impact the offshore construction labor market will have on MOB construction depends on when the MOB will be built. This linkage is due to the cyclic nature of the oil service and construction industry. If a MOB is built during an off peak time in the oil industry, labor may not be a problem due to a potential excess of skilled labor. Yet if construction occurs during a boom period, skilled labor will most likely be in critical supply. Data that are available from Bureau of Labor Statistics (BLS) can be used to establish an estimate of personnel engaged in offshore construction. This data demonstrates the cyclic nature of the oil industry and if MOB construction coincides with an oil boom such as that which occurred in the late 1970's to early 1980's offshore construction labor will be a critical resource.

Table 3. Grand Block Build and Load-out Capacity

Concept	Aker Gulf Marine	JR McDermott	Brown & Root
Rigid	Yes	Yes	Yes
Hinged	Likely	Likely	Unlikely
Independent	No	No	No
Flexible Bridge (semi)	Likely	Likely	Unlikely
Steel and Concrete	Unlikely	Unlikely	Unlikely

Personnel Safety

The safety data for the US shipbuilding industry is used to establish safety risks for an industry that would build most of a MOB. According to OSHA, shipbuilding and repairing is an industry with one of the highest incidence rates for injuries. In 1995 it had the highest and in 1996 it had the third highest nonfatal incidence rate for injuries [14]. From this data it can be derived that the shipbuilding and repairing industry has a factor of three higher incidence rates than similar occupations in construction and oil field service. This information highlights the need to quantify safety risk for such a large project that will be performed largely by the shipbuilding industry.

The conclusion drawn from this data as applied to MOB construction is that safe practices must be accounted for during the design and construction of something this large. MOB construction will involve extremely large structures, which is expected to push the limits of man and machine. A preliminary hazard analysis is presented in Ayyub et al [9].

Environmental Risk

The environmental policy that provides guidelines for US government acquisitions is the National Environmental Policy Act (NEPA). It is assumed that any major construction project to support MOB construction will be under the requirements of NEPA. NEPA specifies actions that necessitate performance of an Environmental Assessment (EA) or Environmental Impact Statement (EIS) must be performed before construction can begin. An EA is an analysis to determine the potential impact of a proposed action. It is less rigorous and time consuming than an EIS. An EIS provides a full and unbiased discussion of significant environmental impacts. It informs the public and decision-makers of reasonable alternatives to avoid or minimize adverse environmental impacts. The dissemination of information, discussion and decision phase of an EIS can significantly lengthen the time for some construction projects. In addition selected environmental mitigation alternatives may also add significant time and costs to a construction project.

Several types of hazards are common in the shipbuilding and offshore construction industry, including chemical (welding fumes, solvents, paints, fuels), physical (noise, heat stress), safety (fires, confined spaces, falls, heavy equipment, dropped objects), as well as others. These hazards may impart environmental risk in MOB construction because of their potential effects on to the land, water, air, and ecology of selected sites.

Each of these processes has associated hazards. The magnitude of environmental risk that a MOB construction poses will depend on a particular MOB concept, the site, and method of construction. Building the MOB may require substantial infrastructure improvements. These improvements would typically involve work in and around the waterfront, an area of heightened environmental concern.

The most significant environmental impact could be to dredge the waterways where the largest MOB components would be built and shipped to sea for final assembly. Dredging would most likely only require an environmental assessment if existing waterways have been dredged in the recent past and only need to be dredged deeper. The requirement to perform only an assessment is potentially less likely to impact MOB construction cost and schedule. The environmental risk is higher if a site must be dredged and the dredged material potentially contains harmful substances. An environmental impact statement and remediation would be required for this activity, thus a potential delay to the construction schedule.

Construction of a new graving dock or any new facility near the waterfront potentially could have a major environmental impact. This is because shipyards have historically been producers of chemicals, heavy metals, and products were not disposed of by conventional methods. Excavation at a major industrial complex has a high probability of unearthing hazardous materials. This activity would certainly require an extensive study and could potentially result in expensive and lengthy remediation.

Construction Management Issues

The construction, shipbuilding, and offshore industry have developed management guidelines to efficiently deliver projects on schedule and within budget by accounting for construction issues in the feasibility and design phase of projects. In the shipbuilding industry this is referred to as "producibility" and in the construction industry this is referred to as "constructability". The following paragraphs are an overview and should be adopted or considered when constructing the MOB. The reader is referred to Ayyub and Bender [13] for a complete discussion of constructability guidelines.

The "build strategy" concept is a recent planning tool championed by the National Shipbuilding Research Program (NSRP) [14] and being implemented by some shipyards. This modern shipbuilding technique tends to minimize redesign and to achieve the lowest costs possible from a production focused design.

Professionals separate from shipyards generally produce the designs of marine systems. The outputs of the design are the plans and specifications that detail the requirements for a MOB. The design can be developed for any shipyard or facility to bid on the work package or be specifically tailored to a particular shipyard. The latter design approach improves constructability and lowers overall risk. Every effort should be made to ensure close coordination between designers and potential builders through the development of a MOB build strategy to facilitate construction. Shipyards need to develop engineering drawings that detail the work instructions of how specific items should be built.

It is assumed that the procedures of ship procurement as practiced by the US Navy will be applied to any MOB construction. It is recommended that all efforts are made to ensure personnel with knowledge of production capabilities and techniques are involved with the procurement process. A team comprised of procurement, design, and production personnel must develop a build strategy. A project as large as the MOB will most likely have components that are built at many facilities. Potential construction facilities for MOB components need to be selected based on the ability of the facilities to construct the block or component sizes contemplated for production.

Although increasing productivity can reduce the exposure to cost and schedule escalation risk, the responsibility for risk reduction rests with management. Additionally, MOB management responsibilities in the feasibility and preliminary design phases should include a performance tradeoff using the principle of cost as an important consideration. The most important function of management once construction begins is to manage and control cost and schedule impacts. The project management tool of earned value could be applied if a MOB was built or alternatively, Bender [15] demonstrated a risk-based earned value technique could be applied to control construction costs.

Any proposed scenario of MOB construction involves several facilities concurrently producing blocks or components for final erection and assembly at a single location. This process requires a management structure in place to maximize coordination, schedule adherence, and minimize rework. The afloat assembly scenario would require a lead design and shipyard or offshore constructor to fulfill this management role. In the terrestrial scenario the assembling shipyard is the lead design and building facility. Due to the complexity and potential for schedule delays when ten or more shipyards are working on a single project, the process of construction management is analyzed as a potential risk in MOB construction.

Preliminary Construction Cost and Schedule Estimates

Preliminary construction cost and schedule estimates were developed for each concept and construction scenario. A database of production indices for US Navy shipbuilding and from other published sources [2, 5, and 11] was established by adapting and populating off the shelf construction estimating software. Each concept was broken down into blocks or components that combined to form components or modules. The established indices were applied to all MOB concepts to document cost and schedule estimates. The preliminary cost and schedule estimates are considered point estimates and were used as a starting point in the cost and schedule simulations.

CONSTRUCTION RISK ANALYSIS

Discrete event simulation is used to perform a construction risk analysis. By analyzing the US capacity and developing scenarios to build a MOB, the following risk areas are accounted for in the construction simulation [16]:

- *Cost and Schedule*
  Account for uncertainty in "point" or preliminary estimates.
- *Labor*
  Marginal strength to construct a MOB and potential competition from existing or future backlog in the shipbuilding and offshore industries.
- *Safety*
  High accident or injury rate could impact cost and schedule.
- *Environmental*
  Potential delay and cost due to environmental studies and mitigation.
- *Construction Management*
  The integration and schedule issues of combining many components from several facilities.

Discrete Event Simulation

Discrete event simulation is defined as "the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time" [17]. In other words the system changes instantaneously in response to discrete events. For example, consider simulating the process of constructing the upper hull of a MOB. Some of the discrete steps are; blocks arrive at an assembly site, blocks are erected, and outfitting is performed until the structure is complete. At each point in the process the variables of time and cost may change. This simulation technique fosters experimentation to determine risk areas to be avoided or accounted for during construction planning.

MOB Model and Simulation Set Up

The discrete event simulation technique is used to assess the probabilistic outcomes of cost and schedule by using statistics to account for the effects of variances and randomness. The model accounts for sequences, construction times, transportation, fabrication and assembly. By accounting for uncertainty, outputs of cost and schedule are developed with associated probabilities. An example of this structure is shown in Figure 1.

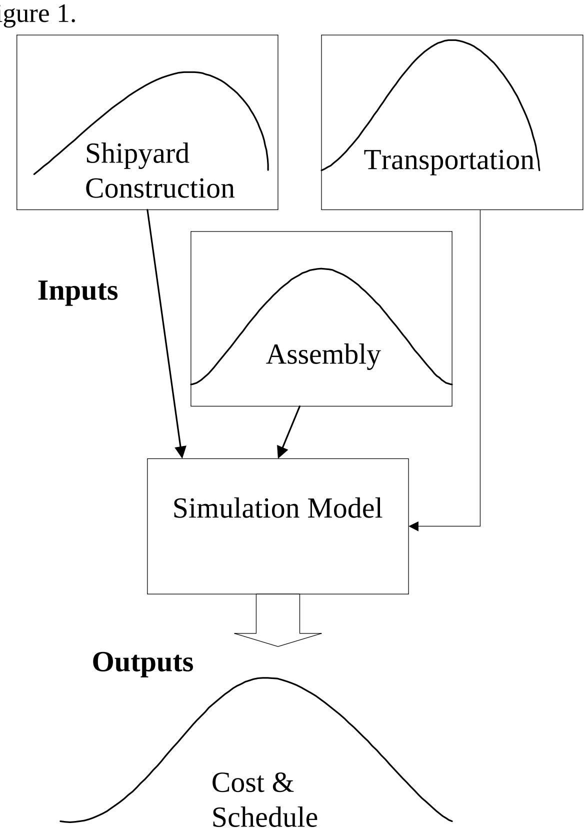

Figure 1. Simulation Set Up

Using the critical path method of construction scheduling, a model is built for a given concept according to the scenario developed in the construction systems definition. Input distributions, as shown in Figure 1, used in the model are based on the particular construction activity. For example building blocks as part of the upper hull were represented by a beta distribution that represented a conservative estimate derived in the construction systems estimate. Selection of other input distributions were based on a review of construction modeling research [18] or applying an understanding of a particular distribution's characteristics and personal construction knowledge.

To perform the many necessary calculations involved in simulation, several software vendors provide programs for discrete event simulations. Extend™ by Imagine That, ® Inc was used to simulate MOB construction. The Extend software was selected because it is easy to use yet it is robust enough to completely model the details of the MOB construction process. Additionally its graphical features make it a useful communication tool to present and document a MOB's construction simulation.

An important step in model building and simulation is verification and validation. Models were built using a collaborative and iterative approach; one member of the modeling team would propose a model and another would critic the model, make necessary changes or propose changes to the model. To verify the model results were correct, simulation results were compared to the estimate found in the construction systems definition. Patterning models after the scenarios critical path schedule validated the model.

The simulation also took into account learning curve efficiencies and the influence of a construction management risk was incorporated into the model with a fuzzy analysis technique as demonstrated in Blair et al [19].

Each MOB construction concept and scenario combination was modeled and simulated. To ensure valid statistics each concept and scenario was simulated with 2000 simulation runs. The results of these simulations employed the central limit theorem to provide a measure of the schedule and cost risk to build a module and are summarized in Tables 4 and 5.

TOTAL MOB COST AND SCHEDULE

Table 6 shows the total schedule and cost of an entire MOB. These schedules for building an entire MOB were extrapolated assuming a simple non-statistical derived schedule overlap of 50%. This assumption is reasonable because it considers the findings in Cybulsky et al. [20] that indicate a schedule overlap for building MOB modules could range from a very conservative 30% to a highly aggressive 80%. These results indicate a MOB will take at least seven years to build and may cost up to $5.5 billion dollars.

CONCLUSIONS

A risk-informed process is used to investigate the construction feasibility of building the five proposed MOB concepts. The results of this work document that the US does indeed have the industrial capacity to build a MOB. Several risk areas have been studied and none of these areas are found to render MOB construction infeasible. It is recommended that any planned construction focus on these risk areas to ensure efficient construction costs and achievable schedules.

Through the use of computer simulation MOB concepts and construction scenarios are explored and costs and schedules have been developed that account for risk areas and uncertainty. These results obtained indicate a MOB will take at least seven years to build and may cost up to $5.5 billion dollars. Even though these values include the time, but not the cost, of outfitting it is felt the schedule and cost are fiscally feasible when compared to other major military platforms.

Should a MOB be built, constructability guidelines have been established and where possible should be incorporated throughout the preliminary design and construction phases of MOB construction. Additionally the build strategy concept should be employed in the construction of a MOB.

Table 4. Simulation Schedule Results

Concept	Scenario	Schedule Results	
		Mean (days)	Standard Deviation
Rigid	Afloat Assembly	754	18
	Terrestrial Assembly	805	17
Hinged	Afloat Assembly	1079	38
	Terrestrial Assembly	1056	27
Independent	Afloat Assembly	1205	35.3
Flexible Bridge	Semisub-mersible Afloat Assembly	1146	20
	Semisub-mersible Terrestrial Assembly	1192	29
	Bridge Truss Assembly	1058	29
Steel & Concrete	Afloat Assembly	912	17
	Terrestrial Assembly	842	25

Table 5. Simulation Cost Results

Concept	Scenario	Cost Results	
		Mean (million $)	Standard Deviation
Rigid	Afloat Assembly	299	6
	Terrestrial Assembly	304	5
Hinged	Afloat Assembly	843	14
	Terrestrial Assembly	804	18
Independent	Afloat Assembly	1516	26
Flexible Bridge	Semisub-mersible Afloat Assembly	1088	30
	Semisub-mersible Terrestrial Assembly	1057	31
	Bridge Truss Assembly	1080	28
Steel & Concrete	Afloat Assembly	991	25
	Terrestrial Assembly	956	26

Table 6: Total MOB Schedule and Cost

Concept	Scenario	Schedule (years)	Cost ($$10^6$)
Rigid	Afloat	9.4	1,794
	Terrestrial	10.1	1,824
Hinged	Afloat	11.4	4,215
	Terrestrial	11.1	4,020
Independent	Afloat	8.0	4,548
Flexible Bridge	Afloat	7.6	5,424
	Terrestrial	7.9	5,331
Steel & Concrete	Afloat	7.9	3,964
	Terrestrial	7.3	3,824

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